

Do all O stars form in star clusters?

Carsten Weidner¹, Vasilii V. Gvaramadze^{2,3,4}, Pavel Kroupa⁴, and Jan Pflamm-Altenburg⁴

¹ Scottish Universities Physics Alliance (SUPA), School of Physics & Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS, Scotland, UK

² Sternberg Astronomical Institute, Moscow State University, Universitetskij Pr. 13, Moscow 119992, Russia

³ Isaac Newton Institute of Chile, Moscow Branch, Universitetskij Pr. 13, Moscow 119992, Russia

⁴ Argelander-Institut für Astronomie (Sternwarte), Auf dem Hügel 71, D-53121 Bonn, Germany

Abstract

The question whether or not massive stars can form in isolation or only in star clusters is of great importance for the theory of (massive) star-formation as well as for the stellar initial mass function of whole galaxies (IGIMF-theory). While a seemingly easy question it is rather difficult to answer. Several physical processes (e.g. star-loss due to stellar dynamics or gas expulsion) and observational limitations (e.g. dust obscuration of young clusters, resolution) pose severe challenges to answer this question. In this contribution we will present the current arguments in favour and against the idea that all O stars form in clusters.

1 Introduction

Besides huge efforts observationally and theoretically, the question how massive stars ($m > 10 M_{\odot}$) form has not been answered satisfactory yet. Amongst others, two main theories of the formation of massive stars have been put forward. One theory being the monolithic collapse of very massive and dense cores (McKee & Tan 2003; Krumholz 2006) into a single star or a binary. As this theory has no requirements for the surroundings of such cores, it allows the formation of isolated O stars without an star cluster associated to them. However, the question how the isolated massive core can form remains open. The other important theory is competitive accretion, where massive stars form in the dense centres of star clusters (Bonnell et al. 1997) and therefore it does not predict isolated O stars.

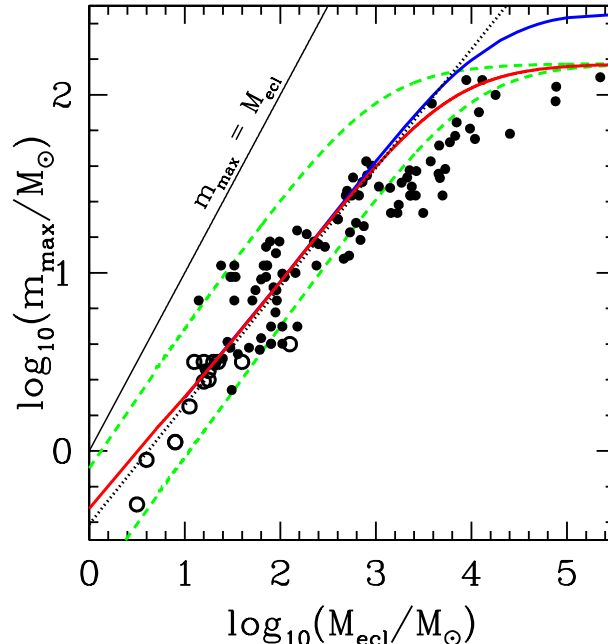


Figure 1: Most-massive star (m_{\max}) in a cluster versus the stellar mass of the young dynamically unevolved “embedded” cluster (M_{ecl}). The filled dots are observations compiled by Weidner et al. (2010), while the open circles are new data from Kirk & Myers (2011). The solid lines through the data points are the medians expected for random sampling when using a fundamental upper mass limit, $m_{\max*}$, of $150 M_{\odot}$ (lower solid, red line) and $m_{\max*} = 300 M_{\odot}$ (upper solid, blue line; Crowther et al. 2010). The dashed lines are the 1/6 and 5/6th quantiles which encompass 66% of the most-massive stars if they are randomly sampled from an IMF with an upper mass limit of $150 M_{\odot}$. The dotted line shows the prediction for a relation by Bonnell et al. (2003) from numerical models of molecular clouds with less than $10000 M_{\odot}$. The thin solid line marks the limit where a cluster is just made out of one star.

Shown in Fig. 1 is a compilation of star clusters from the literature and the most-massive stars in them (Weidner & Kroupa 2006; Weidner et al. 2010). The Figure shows a tight correlation between the mass of the most-massive star, m_{\max} , and the mass of the cluster, M_{ecl} . Especially for massive clusters this m_{\max} - M_{ecl} relation is well below what is expected when randomly sample stars (red solid line) from an stellar initial mass function (IMF). If the formation of massive stars is independent of their natal environment, the m_{\max} - M_{ecl} relation should be well described by random sampling. The existence of a non-trivial m_{\max} - M_{ecl} relation is therefore direct evidence against the formation of O stars in isolation.

But if all O stars are formed in star clusters why do we indeed observe O stars in the Galactic field?

2 Massive field stars

Massive field stars are OB stars that are not members of any currently known star cluster, OB association or star-forming region. So far about 20-30% of all Galactic O stars are in the field (Gies 1987). These stars can be separated into two groups:

- $\sim 25\%$ are high-velocity OB stars (typical $> 30 \text{ km s}^{-1}$; runaway stars; Blaauw 1961; Gies 1987),
- $\sim 75\%$ are low-velocity ($\leq 30 \text{ km s}^{-1}$) OB stars.

Though, have these massive field stars formed in isolation or could they originate from star clusters?

2.1 The origin of runaway OB stars

Generally, high velocity massive field stars OB stars (runaway stars) originate from two mechanisms:

- Disruption of a short-period binary after a supernova explosion (Blaauw 1961; Stone 1991),
- or by three- or many-body interactions in star clusters (Poveda et al. 1967; Gies & Bolton 1986).

Recently, this picture has been expanded by a third mechanism which combines the previously known two ones. In the two-step ejection mechanism, a binary of two O stars is ejected and then later the more massive star in the binary explodes as a supernova, shooting the secondary in a random direction and changing its velocity, too (Pflamm-Altenburg & Kroupa 2010). Such stars can not be traced back to their parent star cluster and will be mistakenly identified as high-mass stars formed in isolation.

Runaway stars can be observationally identified by several direct and indirect methods. The direct methods are based on detection of high ($> 30 \text{ km s}^{-1}$) peculiar transverse and/or radial velocities via proper motion measurements (e.g. Blaauw 1961; Moffat et al. 1998; Mdzinarishvili & Chageishvili 2005; Tetzlaff et al. 2010) and spectroscopy (e.g. Massey et al. 2005; Evans et al. 2006, 2010), respectively. The indirect indications of the runaway nature of some field OB stars are the large ($> 200 \text{ pc}$) separation of these stars from the Galactic plane (e.g. Blaauw 1961, 1993) and the presence of bow shocks around them (e.g. Gvaramadze & Bomans 2008; Gvaramadze et al. 2010, 2011). Fig. 2 shows an example of such a bow shock.

2.2 The origin of low-velocity field OB stars

For low-velocity massive field stars several different origins are possible:

- They formed in isolation,
- they are the low-velocity tail of the ejected stars,



Figure 2: Bow-shock in front of ζ Ophiuchi. Credit: NASA/JPL-Caltech/WISE team.

- there true 3D-velocity has not been determined correctly and they are unrecognised runaways,
- they are members of undetected or dissolved star clusters,
- they are blue stragglers, either directly ejected as such or formed from merged ejected binaries.

It is important to note that a two-step ejection can slow-down or stop runaway OB stars (Pflamm-Altenburg & Kroupa 2010) and therefore let them look like low-velocity field OB stars.

Furthermore, is the definition of runaway stars misleading. The typical velocity of 30 km s^{-1} used to separate runaways from low-velocity stars is an observational definition and not necessarily a typical ejection velocity of stars from a star cluster. Shown in Fig. 3 is the distribution of escape velocities of all ejected stars from a series of 100 *N*body calculations of 500 binaries over 5 Myr. A high-velocity tail certainly exists but in such low-mass clusters these are not massive stars. In total over all 100 *N*body calculations 30 stars ($\sim 10\%$ of the massive stars, each individual cluster has only 3 stars above $10 M_{\odot}$) with masses above $10 M_{\odot}$ have been ejected within 5 Myr. But their escape velocities are only between 7 and 14 km s^{-1} . Though, they still travel between 1 and 50 pc after their escape within the 5 Myr (Weidner et al. 2011).

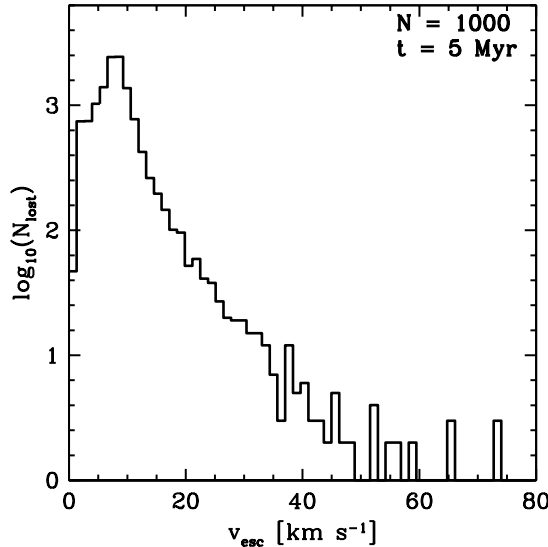


Figure 3: Velocity distribution of all stars (including low-mass stars) escaped after 5 Myrs from 100 star cluster calculations starting with 500 binaries ($M_{\text{cluster}} \sim 340 M_{\odot}$) each (Weidner et al. 2011). Note that the velocity distribution and the escape fraction depends strongly on the initial stellar density of the cluster (see the contribution by Pflamm-Altenburg this volume).

3 High-mass star-formation in isolation?

From an originally proposed fraction of 4% of O stars formed in isolation (de Wit et al. 2004, 2005) careful back-tracking of individual stars (Schilbach & Röser 2008) could reduce this percentage to 2%. Further studies of the five remaining candidates revealed that two of them have bow shocks and are therefore ejected stars, too (Gvaramadze & Bomans 2008). This reduces the fraction of O stars formed in isolation to 1% (Weidner et al. 2011b, submitted). But it should be noted that of the three remaining candidates two cases (HD 193793 and HD 202124) haven't been studied for bow shocks so far. And while in final the case of HD 124314 no bow shock has been found it is important to note that bow shocks are only formed under certain circumstances. Furthermore, does the two-step ejection method predict between 1 and 2% of apparently isolated O stars which can not be tracked back to their natal cluster (Pflamm-Altenburg & Kroupa 2010).

To conclude, there is no significant evidence for massive stars formed in isolation.

Acknowledgments

VVG acknowledges financial support from the Deutsche Forschungsgemeinschaft.

References

- Blaauw, A. 1961, *BAIN*, 15, 265
- Blaauw, A. 1993, in *Astronomical Society of the Pacific Conference Series*, Vol. 35, *Massive Stars: Their Lives in the Interstellar Medium*, ed. J. P. Cassinelli & E. B. Churchwell, 207–+
- Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, *MNRAS*, 285, 201
- Bonnell, I. A., Bate, M. R., & Vine, S. G. 2003, *MNRAS*, 343, 413
- Crowther, P. A., Schnurr, O., Hirschi, R., et al. 2010, *MNRAS*, 408, 731
- de Wit, W. J., Testi, L., Palla, F., Vanzi, L., & Zinnecker, H. 2004, *A&A*, 425, 937
- de Wit, W. J., Testi, L., Palla, F., & Zinnecker, H. 2005, *A&A*, 437, 247
- Evans, C. J., Lennon, D. J., Smartt, S. J., & Trundle, C. 2006, *A&A*, 456, 623
- Evans, C. J., Walborn, N. R., Crowther, P. A., et al. 2010, *ApJ*, 715, L74
- Gies, D. R. 1987, *ApJS*, 64, 545
- Gies, D. R. & Bolton, C. T. 1986, *ApJS*, 61, 419
- Gvaramadze, V. V. & Bomans, D. J. 2008, *A&A*, 490, 1071
- Gvaramadze, V. V., Kroupa, P., & Pflamm-Altenburg, J. 2010, *A&A*, 519, A33+
- Gvaramadze, V. V., Pflamm-Altenburg, J., & Kroupa, P. 2011, *A&A*, 525, A17+
- Kirk, H. & Myers, P. C. 2011, *ApJ*, 727, 64
- Krumholz, M. R. 2006, *ApJ*, 641, L45
- Massey, P., Puls, J., Pauldrach, A. W. A., et al. 2005, *ApJ*, 627, 477
- McKee, C. F. & Tan, J. C. 2003, *ApJ*, 585, 850
- Mdzinarishvili, T. G. & Chageishvili, K. B. 2005, *A&A*, 431, L1
- Moffat, A. F. J., Marchenko, S. V., Seggewiss, W., et al. 1998, *A&A*, 331, 949
- Pflamm-Altenburg, J. & Kroupa, P. 2010, *MNRAS*, 404, 1564
- Poveda, A., Ruiz, J., & Allen, C. 1967, *Boletín de los Observatorios Tonantzintla y Tacubaya*, 4, 86
- Schilbach, E. & Röser, S. 2008, *A&A*, 489, 105
- Stone, R. C. 1991, *AJ*, 102, 333
- Tetzlaff, N., Neuhauser, R., Hohle, M. M., & Maciejewski, G. 2010, *MNRAS*, 402, 2369
- Weidner, C., Bonnell, I. A., & Moeckel, N. 2011, *MNRAS*, 410, 1861
- Weidner, C. & Kroupa, P. 2006, *MNRAS*, 365, 1333
- Weidner, C., Kroupa, P., & Bonnell, I. A. 2010, *MNRAS*, 401, 275